HIGH ENERGY DENSITY CAPACITORS FOR PULSED POWER APPLICATIONS

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Abstract

The improvement in the performance of high energy density capacitors used in pulsed power has accelerated over the past few years. This has resulted from increased research sponsored by the US Army Research Laboratory, in support of the US Military's needs. The capacitor development effort will be discussed as well as the results of both short term and long term testing of a new generation of high energy density capacitors.

I. PROGRESS IN CAPACITOR ENERGY DENSITY

The field of high energy density capacitors encompasses a range of requirements. One of the focus areas of the US Army Research Laboratory (ARL) has been the high efficiency capacitors that are used in electro thermo chemical (ETC) Gun and electromagnetic railgun applications. Typically these capacitors are specified to survive 1000 shots which roughly matches the life of a gun barrel or 10k shots which roughly matches the life expectancy of a Navy gun system. Figure 1 plots the progress in energy density of high efficiency capacitors designed for this type of application over the past four decades.

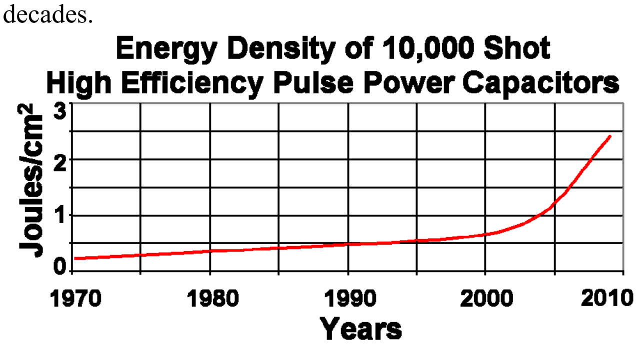

Figure 1 – Progress in the energy density of high efficiency capacitors

The noticeable improvement in the rate of progress in the past five years is a direct result of the research funded by the ARL in this area of interest. As a result of this effort, the US Military has access to capacitors that are about a third the size and half the cost of the capacitors that were available at the beginning of the program. This technology is used in the GA-ESI Type CMX capacitor line.

Figure 2 is a plot of the change in capacitance vs. charge/discharge cycles or shots where the discharge pulse rise time was in the millisecond regime. The data from 6 capacitors shows a well behaved controlled loss of capacitance down to 5% in 55k shots. Five percent is the traditional definition of failure for this type of capacitor. The capacitors are self healing and survive thousands of dielectric breakdowns before getting to 5% capacitance loss. The capacitors are still operational at that point but the build up of gas in the capacitor increases the likelihood of the capacitor failing in an unacceptable manner when the capacitance loss exceeds 5%.

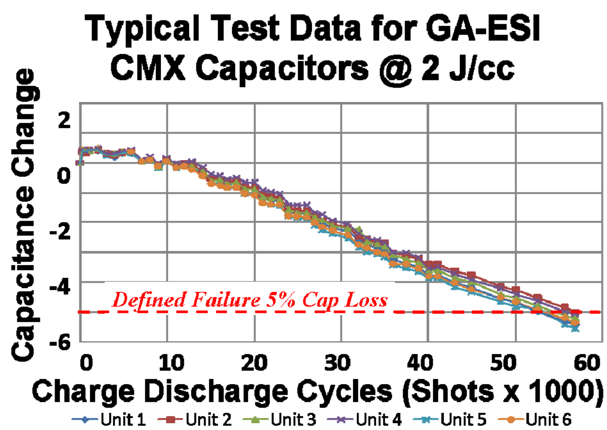

Figure 2 – Capacitance loss of CMX capacitors under pulse discharge duty

The data in Figure 2 are for CMX capacitors operating at 2 J/cc. The energy density for a capacitors that will survive 10,000 shots is 2.4 J/cc for the CMX capacitors. When the capacitors are operated at 3 J/cc

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2009	**N/A**	**-**

4. TITLE AND SUBTITLE
High Energy Density Capacitors For Pulsed Power Applications

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
General Atomics Electronic Systems, Inc. 4949 Greencraig Lane, San Diego, CA 92123-1675 USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.

14. ABSTRACT
The improvement in the performance of high energy density capacitors used in pulsed power has accelerated over the past few years. This has resulted from increased research sponsored by the US Army Research Laboratory, in support of the US Militarys needs. The capacitor development effort will be discussed as well as the results of both short term and long term testing of a new generation of high energy density capacitors.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

they will survive 1000 charge discharge cycles. A plot of life expectance vs. energy density can be found in Figure 3. In the range shown, the life expectancy is following the 20th power rule of the applied field.

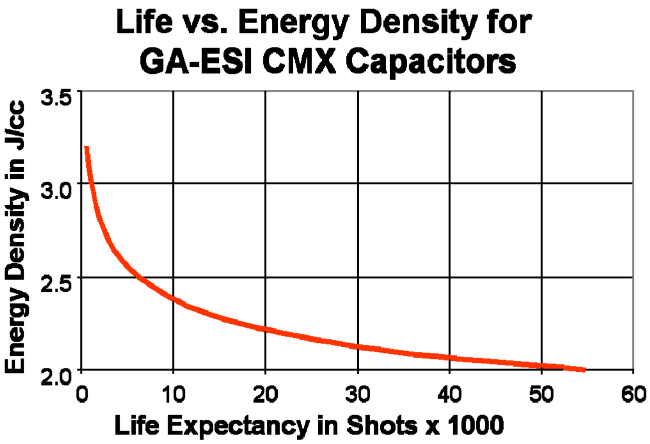

Figure 3 – Energy density of millisecond discharge CMX capacitors

Capacitor performance is sometimes specified in terms of the DC life. Figure 4 is test data for three CMX capacitors tested at 2 J/cc under DC voltage conditions. The capacitors survived more than 400 hours, however it should be noted that the slope of the curve changed once the testing got beyond that point. This could be an indication that a new failure mechanism has been introduced.

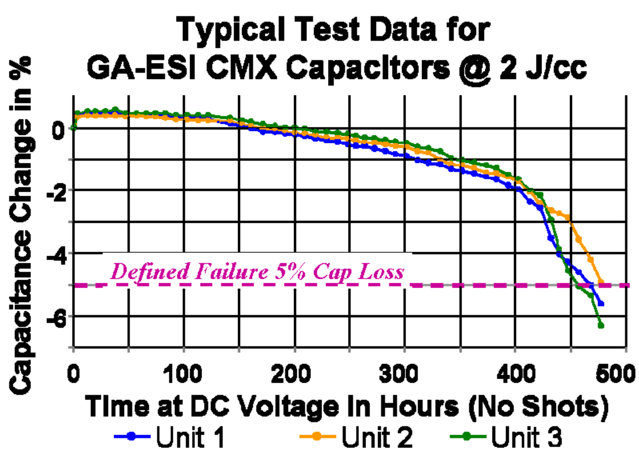

Figure 4 – Capacitance loss of CMX capacitors in DC applications at 2 J/cc

Some applications require significantly longer DC life than can be achieved at 2 J/cc. Figure 5 is a plot of a capacitor using the CMX technology operating at 1.3 J/cc. The capacitor survived for about 3000 hours. The testing was done for about 8 hours a day during normal work days and took several years to complete.

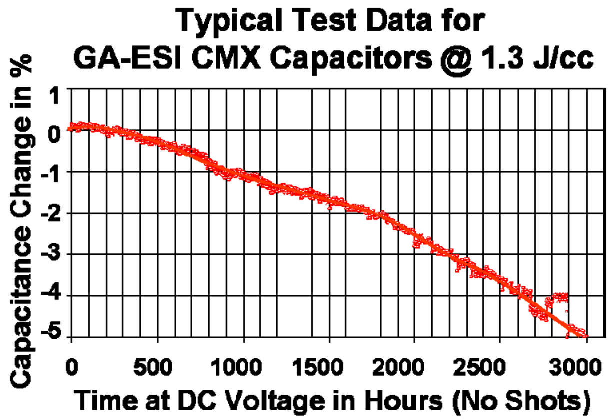

Figure 5 – Capacitance loss of CMX capacitors in DC applications at 1.3 J/cc

The data of Figure 5 represents a significant improvement in the DC life characteristics of this type of capacitor. Previous capacitors lasted only a few hours at energy densities of 1.3 J/cc and this was improved to several thousand hours over the course of the ARL development effort.

II. RELIABILITY AND SAFETY FOR HIGH ENERGY DENSITY CAPACITOR SYSTEMS

The achievements in high energy density capacitors has been a significant contributor to the success of fieldable military pulse power systems. This has brought a number of new concerns to light. The capacitor shown in Figure 6 has a number of features that were developed as solutions to some of these problems.

Figure 6 – Microsecond discharge capacitor with internal dump resistor

The capacitor of Figure 6 has two sets of terminals each with parallel bar terminations. This was needed to facilitate a low inductance, high current connection to the rest of the equipment. The schematic for this capacitor is similar to that shown in Figure 7. There are separate high voltage, low current, terminals for charging the capacitor marked “+” & “-” with high voltage lead wires that will connect to the control circuit.

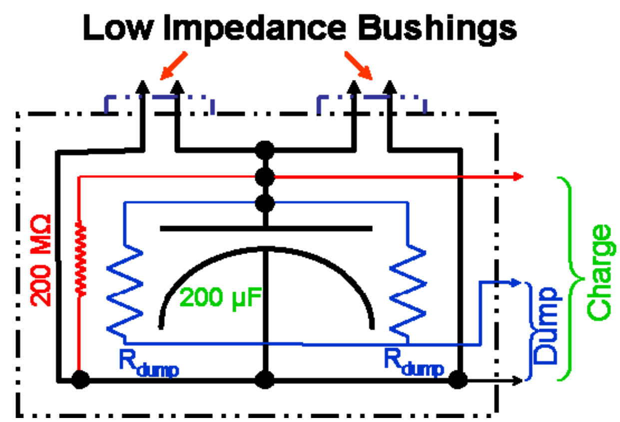

Figure 7 – Typical schematic for the capacitor in Figure 6 (Patent Pending)

The capacitor of has an internal dump resistor, “R_{dump}” of Figure 7 that is connected to a third high voltage low current terminal marked “R” in Figure 6. A low current dump switch in connected between the “R” terminal and the “-” terminal in order to safely dump the energy stored in the capacitor when the circuit is shut down. This unique circuit takes up very little room inside the capacitor and use the thermal mass of the capacitor to absorb the dump energy.

The resistance value of the dump resistors shown in Figure 7 is chosen based on the peak current capability of the dump switch and consideration of time to discharge the capapacitor to a safe voltage. Typically the bleed-down time is of concern until the capacitor voltage is 50 volts or less. The bleeddown time for various resistors in a 200uF 15 kV capacitor application is shown in Figure 8.

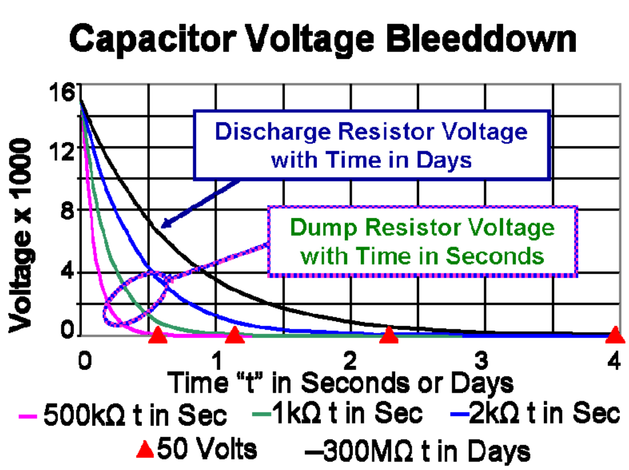

Figure 8 – Voltage bleeddown from 15kV with various discharge resistors

The development of internal dump resistors was spurred by concerns about external dump resistor in terms of shock and vibration, mounting requirements, total volume, system reliability, and cost. All of these parameters were improved with the advent of the internal dump resistor.

Along with the internal dump resistors, there is a 200MΩ discharge resistor shown in Figure 7. This is a fixed resistor that will bring the voltage in the capacitor from 15 kV to 50 volts in about 4 days. These high energy density capacitors have a deeply stored charge that can come to the surface after the capacitor has been discharged. The discharge resistor will minimize the voltage that the capacitor can reach after it has been discharged.

There is always a concern about operator safety with high energy pulsed power systems. There is little observable difference between a charged and uncharged capacitor. In the laboratory, external devices like that shown in Figure 9 are added to the circuit so that the operator will have a local indication that the capacitor is charged. If the normal shutdown circuit does not work properly, the relaxation oscillator will still be blinking and buzzing indicating that the capacitor is still alive.

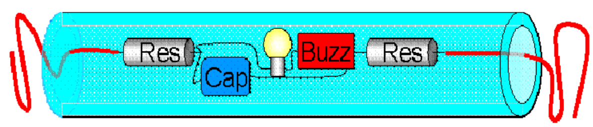

Figure 9 – Sketch of a high voltage warning circuit based on a neon lamp relaxation oscillator in a Lexan® tube

The need to identify a charged capacitor becomes more acute in a military operating theater. The equipment will be going into harms way and is likely to sustain damage. The first responders are likely to have only a rudimentary understanding of the system rather than an electrical engineering degree. The circuit of Figure 10 is designed to minimize this problem. It is the schematic of a 50 kJ 10 kV capacitor with an internal charged capacitor warning system. The schematic has two relaxation oscillators connected in series. The oscillator on the left consists of a small capacitor and a neon lamp what will flash continually at voltages in the hundred volt range but will be on continually when the capacitor is at 10kV. The relaxation oscillator on the right in Figure 10 has a significantly larger capacitor, a neon lamp and a buzzer. This oscillator will store more energy than the circuit on the left and deliver a brighter flash and audible sound less often than the oscillator on the left. At full voltage the oscillator on the right will be flashing and buzzing. In the hundred volt range, it will be doing the same thing but with long pauses between operations. A typical location of the indicating lamps is shown in Figure 11.

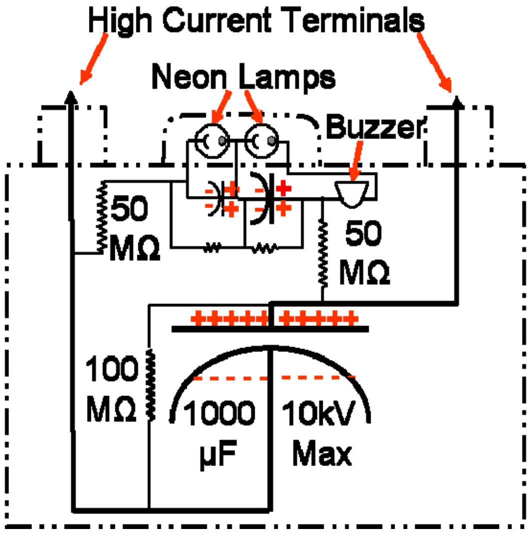

Figure 10 – Schematic of a capacitor with an internal charged capacitor warning circuit based on a neon lamp relaxation oscillator (Patent Pending)

Figure 11 – Typical capacitor with an internal charged capacitor warning circuit

The charged capacitor warning circuit mounted internally to the capacitor to minimize the probability that the circuit will become disconnected from the capacitor. The environment of the capacitor provides electrical insulation and thermal mass for the circuit. It also provides a significant measure of protection from shock and vibration on a deployed system.

III. STATE OF THE ART FOR HIGH ENERGY DENSITY CAPACITOR AND NEAR TERM PROJECTIONS

The improvement in performance of energy discharge capacitors in the areas of focus has been described above. The improvements have made pulse power equipment smaller and more affordable. The goals of the program have been met. The rate of improvement in the two areas discussed is expected to slow due to a lack of funding to pursue the technology. The focus of the development effort has shifted to much faster capacitors and capacitors operating in hostile environments.

The progress in pulse power capacitors is often plotted on a Ragone plot of specific energy vs. specific power. This has been done for today's capacitor in Figure 12. The capacitors plotted include capacitors used in microsecond discharge applications, and capacitors used recently in large applications are included in the plot. The plot includes a time scale is representative of the period of time in which the energy is delivered.

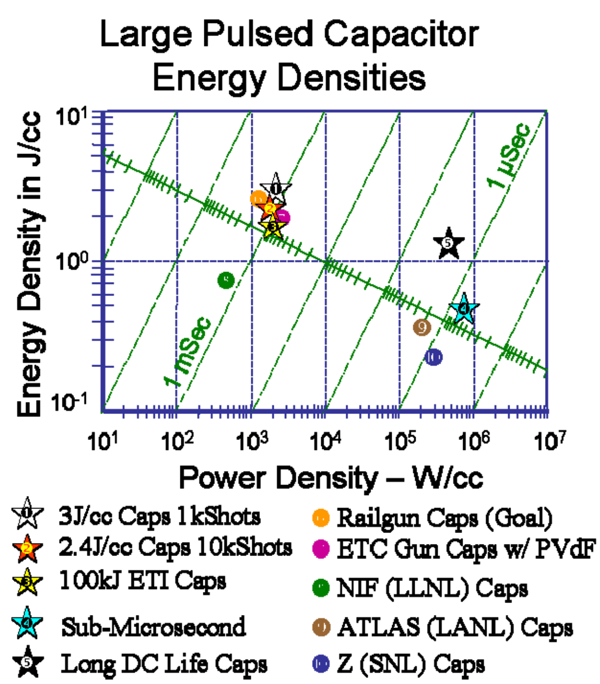

Figure 12 - **Ragone Plot for High Energy Density Capacitors**

The area of greatest interest to the military today is the nanosecond to millisecond range. There are commercial applications in this range but they are not mobile and there is little penalty to be paid for doubling the volume of the equipment. Most military applications are mobile and the logistics of moving and supplying such systems exact a premium on size, weight and efficiency. Because of this difference in needs of commercial and military applications, it is not likely that high energy density capacitor development will go forward with out support from the military.

IV. SUMMARY

Significant progress has been made in high energy density energy storage capacitors. High efficency capacitors are available with energy densities as high as 3 J/cc for 1000 shots or 3000 hours of DC life at 1.3 J/cc. While progress has been significant over the past few years, it is not expected to continue at the same rate due to a change in focused areas of interest on the part of the US military. The development effort at GA-ESI will be aimed at other applications.

V. ACKNOWLEDGMENT

Portions of the research reported in this document/presentation was performed in connection with contract W911QX-04-D-0003 with the U.S. Army Research Laboratory. The views and conclusions contained in this document/presentation are those of the authors and should not be interpreted as presenting the official policies or position, either expressed or implied, of the U.S. Army Research Laboratory or the U.S. Government unless so designated by other authorized documents. Citation of manufacturers' or trade names does not constitute an official endorsement or approval of the use thereof. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation hereon.

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